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Hydro*Star

A Direct Water-Cooled DD-Fueled IFE Fusion-Chamber Concept

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Abstract

We introduce a new IFE fusion-chamber concept called Hydro*Star that uses DT-ignited DD targets and a water blanket. The driver can be either a 13 to 16-MJ diode-pumped solid-state laser (DPSSL) with fast ignition, or a 4-MJ heavy-ion accelerator operating at a reprate 10 times faster than the fusion chamber to accumulate sufficient energy in storage rings to direct 40 MJ at the target. The driver employs a prepulse system to burn an ionized path through the ambient fusion-chamber vapors, whose operating pressure is about 20 atm. We assume that the targets, which have a yield of about 2800 MJ, can be indirectly driven with two-sided illumination. The blanket, which is 1 to 2-m thick and placed immediately inside the structural wall, is operated just over 100 C either in a liquid or frothed-liquid state, the latter being preferred to reduce stresses in the structural wall. The structural wall, at a radius of 4 to 5 m, is composed of low-carbon steels to avoid the stress-corrosion cracking problems that have plagued certain light-water-reactor (LWR) systems. The functions of the blanket are (1) to shield the structural wall and exterior components from neutron and gamma-ray target emissions, and (2) to supply water for the direct generation of steam. Each fusion pulse vaporizes nearly one-half centimeter of the inside surface of the water blanket, thereby creating hot steam which is vented directly from the fusion chamber into ordinary steam turbines. Thus, Hydro*Star operates just like a simple steam engine, with a basic reprate of only 0.8 Hz per GWe of net output. Because the steam temperature is 900 to 1200 K, the plant thermal efficiency is nearly 50%. This efficiency is much better than the typical 35-40% now being achieved in commercial reactors, and much better than the efficiencies estimated for previous fusion-chamber concepts except CASCADE (55%). Other advantages for the new concept include reduced plant radioactivity (reduced radionuclides inventory), longer component lifetimes, nearly self-cleaning operation, reduced risk for catastrophic accidents, and potentially lower cost of electricity. Although Hydro*Star has many advantages, we identify many serious design issues that require future investigation. These include the problems associated with (1) how to interface the evacuated driver beam lines to the high-pressure fusion chamber, (2) how to propagate the driver beams through the high-pressure steam, and (3) how to obtain the necessary tritium supplies without breeding tritium in the water blanket.

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Concept Summary

We propose a new concept of a fusion chamber for inertial fusion energy (IFE) utilizing driver beams from either a diode-pumped solid-state laser (DPSSL) or a heavy-ion (HI) driver. The chamber is operated at high pressure, and features DT-ignited DD fuel targets, a (frothed) water blanket, and direct steam power conversion. Because of its water blanket, Hydro*Star operation avoids any significant vaporization, condensation, and neutron deterioration of structural wall materials. In brief, a 1-GWe Hydro*Star operating at 0.8 Hz has the following features (see Fig. 1 and Tables 1 and 2):

<u>Driver</u> — either a 13 to 16-MJ 0.826-Hz DPSSL operating with fast ignition (DD target gain $G_{DD} = G_{DT} * (347/340)*[(\rho\Delta r+5.5 g/cm^2)/(\rho\Delta r+60\ g/cm^2)]$ with DT target gain $G_{DT} = 400\ E_{dr}^{0.4}$ for driver energy E_{dr}, see Ref. 5), or a 4-MJ HI accelerator operating at 8.26-Hz to accumulate sufficient energy in storage rings to direct 40 MJ at a target at 0.826 Hz. A prepulse system clears channels through the high-pressure fusion-chamber vapors before each pulse on target. Each HI beam is focused outside the fusion chamber before passing through the 3-mm hole in the ~1.5-m-long baffled diaphragm system separating the high-pressure fusion-chamber environment from the beam-tube vacuum. Each beam is transported to the target inside the ionized column created by the prepulse system. The selection of beam ion (Z>50, A>130) has not yet been made. For a DPSSL, the wavelength is assumed to be 0.35 to 0.50 μm.

<u>Target</u> — an advanced design using DT-ignited DD fuel (D^3He could be used if it becomes available). We assume that the targets are indirectly driven with two-sided illumination (i.e., each target consists of a capsule mounted inside a hohlraum). The targets are assumed to have a gain of ~180 (DPSSL) or ~70 (HI) thereby producing a yield of ~2.8 GJ per target for either driver type.

<u>Containment Vessel & Blanket</u> — a 3-to-5-m-radius, nearly spherical, vented, low-carbon-stainless-steel vessel lined with a 1-m to 2-m-thick blanket of water. The water is supported by a compartmental or wick substructure that prevents unrestricted gravitational flow. The preferred mode of blanket operation (although not necessarily essential) is with many small compressible vapor bubbles in the water, thus creating a frothed water blanket that reduces wall stresses. The containment vessel reprate and size can be adjusted to obtain the desired dynamical water vapor chemistry at $T \approx 900$ to 1200 K and the desired turbine pressure.

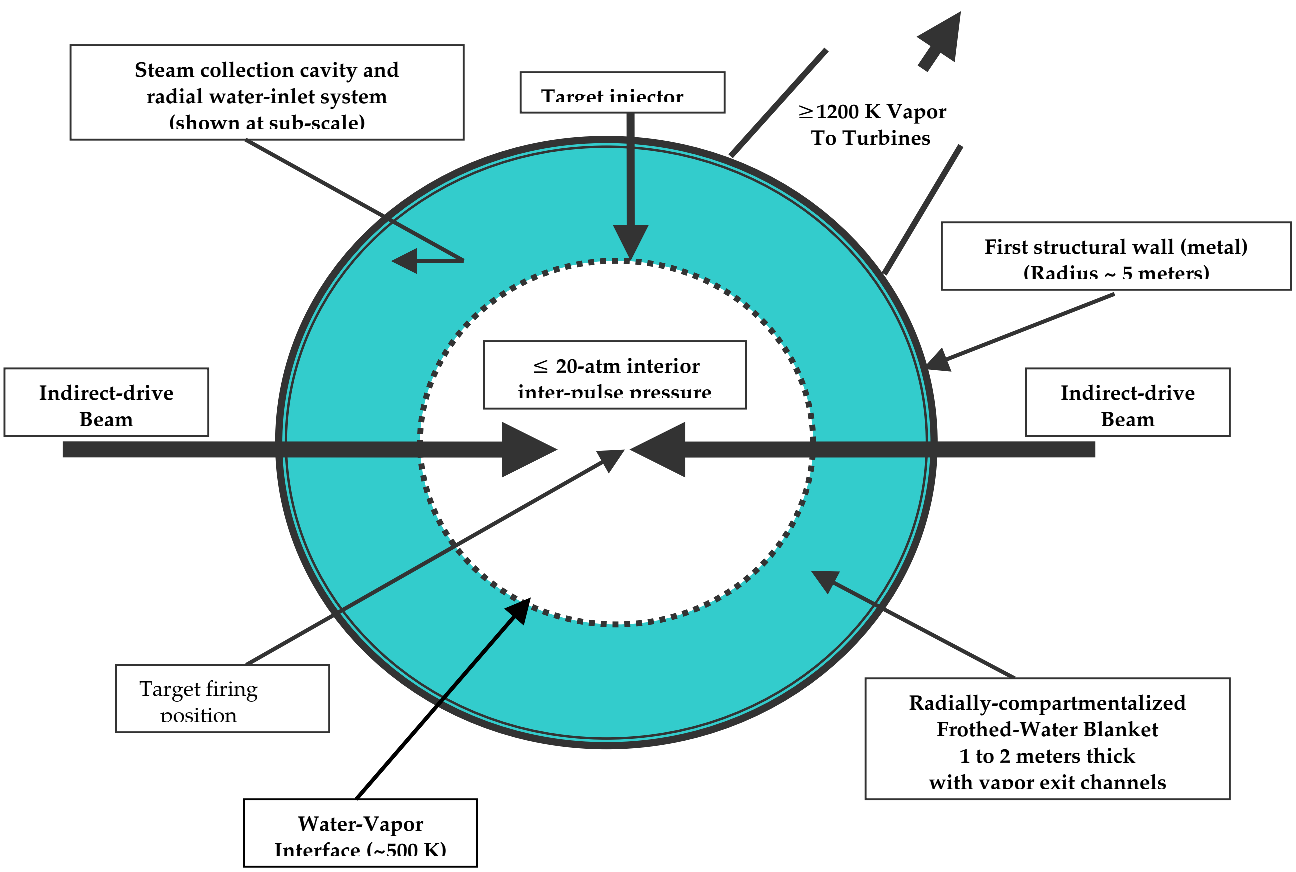
<u>Power-Conversion System</u> — ablation and vaporization of the water blanket and direct steam conversion. The vaporized water exits the fusion chamber through its vents and goes directly into metal-bladed turbines. The plant thermal efficiency (70% of Carnot) is about 50%.

<u>Plant Energetics</u> — For every 1 GWe of electrical output, the plant energy and power flow are those described in Table 2. We emphasize that the values shown in Table 2 are merely illustrative for one possible design, in which the chamber contains ≤ 2.9 GJ every pulse, and the plant gross thermal power is ≤ 2.5 GW with recycled power fractions of 17% or less. The optimum plant output power has not yet been established.

Table 1 Main Features of Hydro*Star

- Self-cleaning protected first wall
- 1 to 2-m-thick frothed-liquid water blanket
- Simplified chamber dynamics with increased target repetition rate
- Direct steam-boiler operation without intermediate heat exchangers
- Manageable tritium consumption and handling
- Plant thermal efficiency of ~50%
- Either DPSSL or HI driver beams
- Lower risk, lower cost, and naturally safer

Figure 1 Conceptual Layout of Hydro*Star.



This concept has many unresolved and difficult design issues, which we will address below. The concept does have many advantages, however, and Table 3 displays a partial list of these advantages.

Table 2 Energy and Power Flow in 1-GWe Hydro*Star at 0.826 Hz

Item	DPSSL Driver (calculated)	HI Driver (estimated)
Driver reprate on target (Hz)	0.826	0.826
Driver internal reprate (Hz)	0.826	8.26
Assumed energy E_{dr} on target (MJ)	16.143	40.00
Driver input power (MW)	203.4	165.1
Driver output power (MW)	13.33	33.02
Driver efficiency	6.55%	20%
Total number of driver beams on target	1231.	(unknown)
Driver total cost (B$)	9.425	(unknown)
Target fuel (DT-hot-spot ignited)	DD	DD
Target gain G (DPSSL with FI)	178.2	69.00 (assumed)
Energy contained per pulse in chamber, including driver energy (MJ)	2,893.	2,800.
Chamber neutron multiplier	1.05	1.05
Gross thermal power (MW)	2,508.0	2,427.3
Plant thermal efficiency	0.50	0.50
Gross electric power (MW)	1,254.0	1,213.7
Fraction of gross electric power sent to auxiliary equipment	4%	4%
Recycled power fraction	16.9 %	14.17 %
Recycled power (MW)	203.4	165.1
Net output power (MW)	1,000.0	1,000.0
Projected COE (cents/kWh)	19.4	(unknown)

Table 3 Advantages of Hydro*Star

(1) Simple direct operation, with water vaporized directly by the fusion pulse and run directly through turbines, just as in a simple steam engine.
(2) Use of a known blanket technology, based on steam.
(3) Reduced plant radioactivity because of less tritium and less induced neutron activation — in fact, the operation becomes nearly self-cleaning.
(4) High thermal efficiency (approximately 50% rather than the typical 35%) because of the direct steam power conversion.
(5) Increased structural wall lifetimes, because of the use of a thick water blanket and advanced fusion fuels having reduced neutron fluences.
(6) Higher plant availability factor because of the above advantages.
(7) Capability for higher reprate operation, corresponding to larger plant output powers for the same construction cost, because the interpulse period is no

	longer as restricted by vapor condensation.
(8)	Reduced risk for catastrophic accidents, because the basic blanket material is just water, which is nontoxic, nonradioactive, nonflammable, safe for the environment, and operating at only ~100–120 C.

Motivation

Previous fusion-chamber designs have generally avoided the use of DD targets because such targets are difficult to ignite and burn with a gain much less than that for DT targets. Use of DT targets, however, requires that the blanket for the containment system have capabilities to absorb neutron energy and breed tritium. The latter requirement severely constrains the available solid and liquid blanket materials, essentially to compounds of lithium. In liquid form, these compounds (1) can have safety hazards due to flammability and/or chemical reactivity, (2) generally require high pumping powers, (3) are usually arranged in complicated geometries, (4) typically introduce uncertainties in their isochoric breakup and condensation, and (5) usually dictate low thermal efficiencies because of their low vaporization temperatures. In solid form, the lithium compounds can be ceramics with which we have little experience. In addition, the abundance of tritium for DT targets causes increased radioactivity problems, even though the ICF concepts have reduced plant radioactivity and reduced safety risks when compared with other fusion or fission concepts. Furthermore, use of DT reduces component lifetimes because of the large fluence of 14-MeV neutrons.

We therefore chose to abandon the reliance on DT fuel. This decision removes the necessity to breed tritium, thereby allowing a wide variety of blanket materials. The safest and cheapest material is probably water, which allows for direct conversion of the ablated and vaporized blanket material through turbines (if the residual tritium level proves to be manageable). We felt that the best configuration for a water blanket would be an annulus directly adjacent to the containment wall and supported in a compartmental or wick substructure (and not a system of isolated fluid jets) because:

(1) Interior jet structures may not break up as much as one might expect under isochoric neutron heating, so they may not be an aid to condensation of vaporized blanket material to facilitate higher reprates, and definitely introduce reprate constraints corresponding to the time to re-establish the jet structure after any shot;
(2) Jet structures involve greater complexity (higher risk) and greater pumping-power losses, and can introduce a potentially serious reprate constraint due to splash;
(3) Solid interior annuli can be accelerated by ablation and/or vaporization pressures and cause serious impact problems for first walls; and
(4) Unconstrained (unwicked) liquid flows at the containment wall at large radii generally involve very large flow volumes and hence large pumping-power expense if recycled using normal pumping methods.

Previous fusion-chamber designs have avoided operation of a containment vessel at pressures above roughly 0.01 Torr to allow the driver beams to propagate without significant attenuation through the ambient vapors preceding any pulse. However, this requirement heavily constrains the containment concepts, so we chose to abandon this requirement as well.

Such a decision shifts the design burden from the multitude of problems associated with the constrained containment concepts to two (serious!) problems associated with Hydro*Star, namely, (1) how to interface the evacuated driver beam lines to the high-pressure fusion chamber, and (2) how to propagate the driver beams through the high-pressure fusion-chamber gas.

Previous fusion-chamber designs have considered laser, HI, or light-ion drivers. Although Hydro*Star might accommodate any of these drivers, we shall consider only HI and DPSSL drivers.

In addition, Hydro*Star is similar to the General Electric Boiling-Water fission system in the sense that the primary heat-exchange fluid is transferred in the vapor state, not in the liquid or solid state. Consequently, Hydro*Star does not need intermediate heat-exchange systems that lower plant thermal efficiency. Another benefit from using the vaporized blanket material directly is that Hydro*Star is thereby free of reprate restrictions due to recombination chemistry and condensation physics associated with trying to obtain a fusion-chamber pressure below 0.01 Torr prior to the next driver pulse, as is required in most other designs. In addition, because the Hydro*Star fluid is water, which has a low vaporization temperature, high Carnot efficiencies can be realized without invoking the use of ceramics, which might prove to be costly and/or risky, especially for turbine blades.

Issues

There are many serious issues that must be addressed with this fusion-chamber concept. We discuss some below, and request the help of readers in discovering others and in overcoming difficulties with those listed here.

Target Gain & Driver Cost

The cost of the driver to ignite DD fuel targets is a serious issue because the driver energy for DD targets must be substantially larger than for DT targets for the same target gain. Although the only way to establish the optimum parameters for such things as the target gain and the driver efficiency is through a detailed cost analysis of all plant systems, it is possible to determine approximate relationships through a simplified analysis as follows. Independent of the fusion-chamber reprate (or the number of targets ignited simultaneously per driver pulse), the so-called fusion cycle gain is

$$\eta(G+1)M\varepsilon_{th} = \frac{1}{0.96\,f} \tag{1}$$

where η is the driver efficiency, G is the target gain (G+1 includes the driver energy), M is the blanket energy multiplication factor (typically 1.15 for past blankets, but not yet calculated for water, so we conservatively use 1.05), ε_{th} is the power-conversion thermal efficiency, f is the recirculated power fraction to run the driver, and the 0.96 assumes a 4% loss of gross electric power to operate auxiliary systems. For example, with $M \approx 1.05$ and using $f = 0.10$, we get

$\eta G \varepsilon_{th} \approx 10$. Normally ε_{th} is about 0.35, so ηG would be near 30. [Note that ηG estimates do in fact proceed from Eq. (1) and *not* from an economic analysis because fusion-chamber ("reactor") construction costs are not linearly related to plant thermal power].[1] As shown below, however, the Hydro*Star concept allows $\varepsilon_{th} \approx 0.50$, so we desire $\eta G \approx 20$ (we probably *need* only half this, corresponding to an f of 20%). With a HI driver operated with storage rings and a prepulse system as described below, we assume $\eta \approx 0.20$ so the target gain must be 50 to 100 to satisfy simplified plant economics. We shall conservatively assume a gain of 70 including the HI driver energy itself (i.e., G+1 = 70).

Current indications suggest that G is expected to be about 70 for both laser[2] and heavy-ion[3] targets that use DT fuel and a driver energy of 5 to 10 MJ. Target gain is given by

$$G = \frac{M_{\rm fuel} E_{\rm TN} \Phi}{E_{\rm dr}} \tag{2}$$

where $M_{\rm fuel}$ is the mass of fusion fuel, $E_{\rm TN}$ is the fusion energy released per unit mass (340 MJ/mg for DT; 347 MJ/mg for DD, assuming that all of the produced tritium and ^{3}He burn; and 353 MJ/mg for D^{3}He), Φ is the fuel burn-up fraction,

$$\Phi = \frac{\rho \Delta r}{\rho \Delta r + \Psi} \tag{3}$$

$E_{\rm dr}$ is the energy of the driver, $\rho\Delta r$ is the compressed fuel column density, and Ψ is a fuel-dependent and burn-temperature-dependent constant. For DT fuel, Ψ is 6 g/cm^2 for burn temperatures near 80 keV. For DD fuel, Ψ is about 60 g/cm^2 for 80 keV, but 40 to 30 g/cm^2 for 200 to 300 keV, respectively (see Fig. 2). Therefore, if DD and DT targets have the same fuel mass, the same $\rho\Delta r$ (e.g., about 3 g/cm^2), and the same burn temperatures, then the gain for a given driver energy should be a factor of 7 lower for the DD target [because the DT target has $\Phi = 3/(3 + 6)$ while the DD target has $\Phi = 3/(3 + 60)$].

We need not accept such low gains for DD targets, however, for several reasons. First, although a DT reaction produces 80% of its 340 GJ/g of yield in fast neutrons,

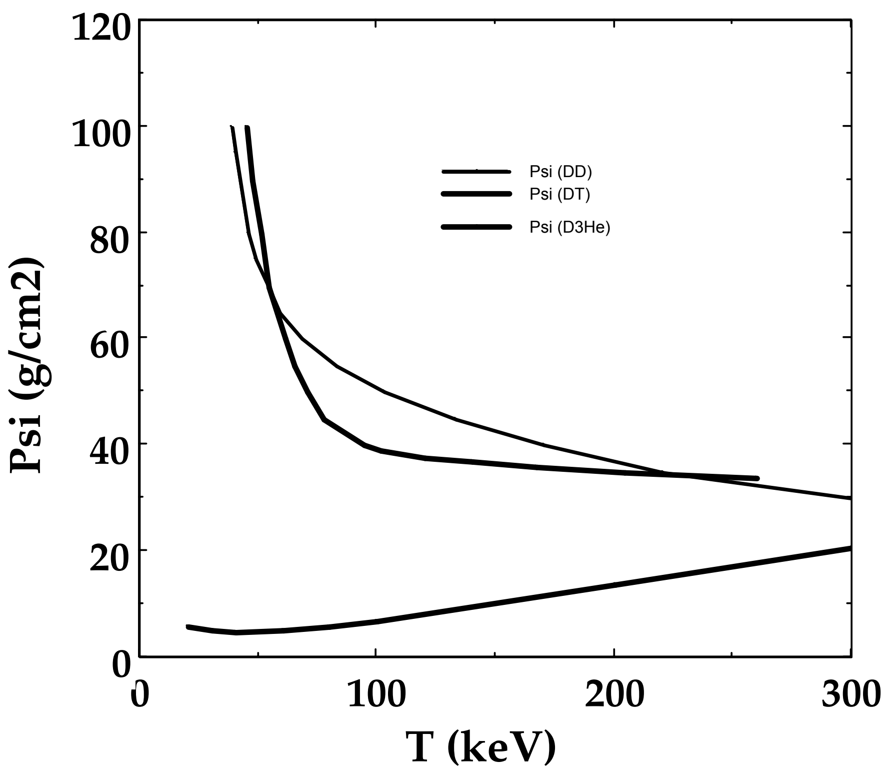
$$\mathrm{D} + \mathrm{T} \rightarrow (3.5\text{-MeV})\,\alpha + (14.1\text{-MeV})\mathrm{n} \tag{4}$$

a DD reaction produces only two-thirds of its 347 GJ/g of yield in fast particles

$$\begin{gathered} 6\mathrm{D} \rightarrow (3.5\text{-MeV})\,\alpha + (3.6\text{-MeV})\,\alpha + (2.45\text{-MeV})\mathrm{n} + \\ (14.1\text{-MeV})\mathrm{n} + (3.02\text{-MeV})\mathrm{p} + (14.7\text{-MeV})\mathrm{p} + 1.83\ \mathrm{MeV\ K.E.} \end{gathered} \tag{5}$$

assuming that the DD reactions are fully catalyzed (i.e., the tritium and ^{3}He that are produced burn completely). We can thus increase the size of the DD fuel mass, and the target would stop a significantly larger portion of the fusion energy, thereby affording a higher burn temperature and a lower Ψ in Eq. (3) (see Fig. 2). This would make the gains for DT and DD targets for a given driver energy differ by less than a factor of 7. In addition, there are advanced design concepts that allow DD target gains near 70, but for larger driver energies (i.e., larger ignition thresholds). Target gain for standard designs scales with driver energy according to the old relationship[4] $G \approx E_{dr}^{1/2}$ or the more current relationship[2] $G \approx E_{dr}$, where the exponents on E_{dr} in both relationships tend to decrease towards higher E_{dr}; however, G for advanced DD designs can have a completely different dependence. The correct dependence on E_{dr} must be determined before we know how much to increase E_{dr} to offset the lower gain expected for DD targets. We estimate, however, that E_{dr} must be less than the product of the 5 to 10 MJ estimated for E_{dr} for standard designs and the factor of 7 that would be dictated by $G \approx E_{dr}$ to make up the maximum factor of 7 difference in gain. For the discussion here, we assume that E_{dr} must be 40 MJ for the DD targets used with a HI driver.

Figure 2: Ψ in Eq. (3) as a function of fuel burn temperature.



For a DPSSL driver using fast ignition[5] (FI), we have chosen an old DT gain curve via Ref. 5 as $G_{DT} = 400\ E_{dr}^{0.4}$ and scaled this by Eqs. (2) and (3) to get the DD gain curve $G_{DD} = G_{DT} * (347/340)*[(\rho\Delta r+5.5 g/cm^2)/(\rho\Delta r+60\ g/cm^2)]$. FI is a speculative target-ignition scheme with many unresolved issues, especially the overall gain curve, so the gains used here are merely illustrative. FI employs a capsule compression (with most any driver) that is less sophisticated than the standard compression, which attempts to achieve a central hot spot in the fuel. The modest compression is followed by a ~200-ps 10^{18} W/cm^2 laser pulse to "channel" through the ablated corona to any part of the compressed fuel, and then a ~30-ps 10^{20} W/cm^2 laser pulse to ignite the fuel through the channel.

The construction cost of a HI driver scales typically as $E_{dr}^{0.4}$, according to Bangerter.[3] According to this scaling, a 40-MJ driver would cost 2.5 times more than a 4-MJ driver. Although it is possible that driver costs might be reduced to accommodate such an increase, it is more advantageous to be creative and try to keep the cost near the 4-MJ-driver level. One way to do this is to reprate the 4-MJ driver at 10 times the reprate of the fusion chamber, with the pulses being stored in suitable storage rings at the end of the driver chain, and then delivered simultaneously to one target. Assuming that the cost of the storage apparatus is much less than the cost of increasing the energy of the whole driver, the cost scales much less than $E_{dr}^{0.4}$, and Eq. (1) is unaffected. Further cost studies are necessary to see if such tricks are viable. We will assume here that they are.

The situation becomes even more tricky, if not impossible, for D^3He fuel. Such fuel is even harder to light (the fusion and Bremsstrahlung rates are equal for temperatures of 4.5 keV for DT, 16 keV for DD, but 38 keV for D^3He). In addition, the cost of ^3He is prohibitive (very limited quantities exist naturally on the earth). We therefore chose to use DD fuel. Nevertheless, D^3He has a similar Q value

$$D + He^{3} \rightarrow (3.6\text{-}MeV)\,\alpha + (14.7\text{-}MeV)\,p^{+}, \tag{6}$$

and a similar E_{TN} (353 MJ/mg); moreover, D^3He has nearly 100% of the fusion release in charged particles (some DD fusion occurs) and has a slightly higher gain than DD at burn temperatures above about 50 keV [see Fig. 2 and Eq. (3)]. Use of D^3He thus does have advantages (e.g., requiring a thinner blanket), so D^3He should be considered whenever it becomes more available. However, Tabak[14] has shown that a 14-MeV neutron from a DT hot spot, which can be used to light D^3He, can convert a ^3He to T which then reacts with a D, thus making most of the yield from D^3He targets arise from DT reactions. Careful calculations of yield products are therefore required.

The cost of targets must also be considered in detail. If advanced DD target designs are required to keep the driver cost acceptable, and we think that they are, there is a serious question whether the advanced target designs can be fabricated at economical cost. Further studies of the target fabrication facility are required.

Wick Operation & Splash

What we designate here as the wick is either a compartmental substructuring of the blanket's water inlets, much like a honeycomb with each compartment having its own water inlet, or an actual wick substructure relying on capillary action. In either case, the purpose is to restrict any free flow of the blanket water under the pull of gravity, thereby avoiding high-volume flows and hence high pumping-power losses. Although design studies are needed to determine whether compartmental substructures are viable, we will assume that they are not, and consider just wick-type substructures.

There are serious questions relating to the wick composition, its mechanical stability, and its lifetime. The water blanket must be supplied with pressurized water throughout its spherical contact with the main containment wall to offset the outward pressure caused by (1) shock impact of the target fireball with the blanket, and perhaps also by (2) some x-ray ablation of the inner surface of the water. The fireball is a hot interior gas region produced because the ambient water vapor is opaque to all of the x rays and most of the charged particles emitted from the target. Expansion of this hot region creates a spherical shock wave much like that from an explosion of HE in the atmosphere. The shock travels outward in the ambient fusion-chamber vapors and impacts the blanket creating an impulse that pressurizes the water. In addition, the isochoric heating from the faster charged particles and the neutrons will cause vibrational loads as the water continually releases its stress due to sudden temperature rises. These temperature rises may be only a few degrees K or less at radii of several meters, but would be larger for smaller fusion chambers. Under all of these conditions, it is not clear that a wick can be designed to support the water mass and not deteriorate due to fatigue and/or radiation exposure. Moreover, it is not clear how much (if any) of the inner surface of the wick would ever be exposed to x rays or extremes temperatures, and thereby be eroded, reducing its lifetime.

In addition, it is desirable (but not necessarily essential) to have compressible voids in the blanket to reduce the shock pressures transmitted to the structural wall. Voids might be fabricated into the wick material, although this option might seriously constrain the wick design and/or materials available. Voids might alternatively be introduced either by operating the blanket in a two-phase vapor-liquid realm or by frothing the water upon its entry into the blanket. A future investigation should address whether frothing is viable and just how it might be accomplished. Frothing is not essential, however, even though it is advantageous, because shocks formed in the water will decay rapidly over the first several millimeters of transit toward the structural wall to a pressure level corresponding to the yield strength for uni-axial strain. Such pressures should be below the spallation threshold for the wall material, even when we consider the shock coupling from the water into the structural wall. However, disruption of the blanket due to shock reflections at the water-wall interface may be an issue, so we must consider such a possibility in future investigations.

The water throughput at 50% thermal efficiency is 0.56 cm/s per GW of plant electrical power, if the inner water surface is at a radius of 3 m and we ignore energy used to dissociate or ionize the vapor (see below). The wick structure must allow for this throughput under continuous operation, but must also accommodate some startup procedure.

Whether there will be water splash to impede the delivery of driver beams for the next pulse is a question needing further study. We assume here that the presence of the wick structure will stabilize the water enough to avoid oscillations that might disrupt the spherical nature of the inner surface and lead to ablative forces or shock impacts that would cause splash. A design with a water annulus at the structural wall is certainly less prone to splash than a design with jets or interior annuli; the question is whether splash is avoided or reduced to a manageable level.

Containment Vessel Vapor Dynamics and Chemistry

For either driver, each pulse produces ~2800 MJ of fusion energy. Because roughly 1/3 of the output is in high-energy neutrons according to Eq. (5), we assume that about two-thirds or 1870 MJ is contained in the spherical volume interior to the water blanket, and that this energy acts to vaporize, dissociate, and ionize water every pulse. Because it takes about 3.7 MJ/kg to vaporize water at 100 C and raise its temperature to 900 to 1200 K, 53 MJ/kg to dissociate water completely, and 220 MJ/kg to ionize water once, one might expect the sum or 277 MJ/kg to represent the net expenditure to remove water from the blanket. This is not true, however, because the ionization and dissociation states merely store the energy until it can be transferred to the first wall (the water). Thus, each fusion pulse releases enough energy to vaporize roughly 1870/3.7 $\approx$ 500 kg of water (i.e., a 4.4-mm thickness at a radius of 3 m). This mass of water in a 3-m-radius cavity produces a density about 3 times atmospheric density (i.e., about 4.4 kg/m^3 = 4.4×10^{-3} g/cm^3, or 1.5 to 4.5 x 10^{20} particles/cm^3, the latter value applying if the vapor is H, H, O). The column density of this vapor along a 3-m radius is 1.3 g/cm^2, and the pressure is about 2040T Pascal (i.e., about 22 atm for T = 1100 K). The mean free path of neutrons in water is about 11 g/cm^2 at 2 MeV and 20 g/cm^2 at 14 MeV. Thus, the vapor will not stop the neutrons. The range of protons in water is 0.015 g/cm^2 at 3 MeV and 0.22 g/cm^2 at 14 MeV. Thus, the vapor (and possibly even the target) will stop most of the protons. The vapor will certainly absorb the x rays, but possible resonance re-emission of the x rays and line transport through the vapor might make the vapor effectively transparent to the x rays at microsecond time scales.

A fusion pulse in Hydro*Star is therefore quite different than in an evacuated fusion chamber, in several respects. First, only about 1/3 of the energy is transported to the blanket in the form of neutrons, not the usual 60 to 80%. This reduces neutron fluences and extends component lifetimes. Second, the near-target absorption of the x rays, target debris, and proton emissions will produce a fireball that transports energy to the blanket primarily through a shock wave (although there may be some radiation too). This makes the Hydro*Star explosion similar to the explosion of TNT in the atmosphere. Although there is more experience with this kind of explosion, it definitely creates more difficulty in trying to contain the fusion processes, which are thereby more hydrodynamic in nature rather than radiative. Third, it is not clear just how much x-ray ablation of the surface of the water will occur. If resonance line transport is not significant, x-ray ablation will be significantly suppressed. Fourth, the ambient state of the fusion chamber is one at high pressure, not the usual 0.01 Torr or less. Nevertheless, the exact dynamics occurring inside Hydro*Star are currently not well known and must be determined through future investigation.

In any case, the end result of every pulse is to vaporize some water and to raise its temperature to one to tens of eV, thereby ionizing and dissociating the water. This hot vapor then cools by vaporizing more water until the rate of heat conduction through the water blanket can match the heat-transfer rate from the vapor. The vapor then cools by blanket heat conduction until reaching the boiling temperature of the water at the ambient pressure. During such cooling, which occurs on a time scale near 1 ms, the energies stored in ionization and dissociation are released through recombination, thereby delaying the cooling. If cooling below the boiling temperature were allowed, condensation would occur.

The vapor that exits the containment vessel through the vents therefore has a composition that depends on its temperature, and therefore on its pressure, but also on the residence time at that temperature. Initially, when very hot, the vapor species include ionized elements and the dissociated species H, H_2, O, O_2, OH, along with H_2O. Water above 3300 K is fully dissociated, while H and O below 800 K will not combine without a catalyst or a flame source.[6] Thus, dissociated hydrogen and oxygen between 800 K and 3300 K will burn depending on the time spent at these temperatures, with a typical burn delay time of perhaps 2 ms. Thus, at any particular temperature, a kinetics computer code must be used to establish the constituents.

The operating temperature (and pressure) of the vapor exiting the fusion chamber through its vents must be chosen with several constraints in mind:

(1) The primary constituent of the vapor entering the turbines should be steam, not an explosive mixture of H_2 and O_2.

(2) The temperature should not exceed about 1200 K, or ceramic turbine blades are required, and cost and risk would thereby increase. The current upper limit to avoid materials problems for the turbines is in fact about 900 K, but some materials development can be expected.

(3) The steam temperature T_{hot} and turbine pressure should both be as high as possible to increase plant thermal efficiency ε_{th}, which is the product of the turbine efficiency ε_{tb} and the Carnot efficiency:

$$\varepsilon_{th} = \varepsilon_{tb} \frac{T_{hot} - T_{cold}}{T_{hot}} \tag{7}$$

We assume that the thermal dump temperature T_{cold} is near 300 K, so the Carnot efficiency is near 70%. For standard steam turbines, which currently operate at 2000 psig (136 atm) with a maximum of 5000 psig (340 atm),[7] the turbine efficiency is composed of a mechanical efficiency above 90% and an electrical-conversion efficiency near 75%, thus making ε_{tb} approximately 70%. Because Hydro*Star operates at only tens of atm, we must determine by how much ε_{tb} is reduced below 70% by having the less efficient turbine operation at the lower pressures. For sure, plant operation (reprate and venting) must be arranged to maximize turbine pressure and not let the chamber pressure drop significantly between pulses (as it otherwise would tend to do).

(4) The steam temperature must not be so high that turbine maintenance decreases the plant availability factor. Current operating temperatures for standard steam

turbines for high availabilities are 1000 to 1050 F (810 to 840 K), with a maximum of 1150 F (900 K).[7] What range will be appropriate in the future is unknown.

(5) The energy required for the prepulse system to prepare a path for the heavy ions can not be large compared with the 40 MJ required by the target, or significant cost could be added to the driver systems. The prepulse energy increases for larger fusion-chamber pressures because larger pressures increase the ambient mass in the beam paths. The prepulse energy also increases for higher ambient temperatures because even higher channel temperatures are required to cause expansions to obtain the channel densities that will permit efficient beam propagation.

With these constraints, it appears as though the maximum steam temperature should be 900 to 1200 K, with 1000 to 1100 K being preferred if we allow for some future materials development. It is for this reason that we have specified the internal chamber pressure to be about 20 atm, in which case the chamber vapor is 0.44 g/cm^2 thick per meter of length. We have not yet run a kinetics code to understand the chemistry at these conditions, but it is extremely likely that such vapor, after transit to the turbines, will not contain hydrogen gas or oxygen gas unless these species have formed unmixed pockets. Issues include (1) the likelihood of fractionation into H_2 and O_2 at bends in the vent pipes and (2) the necessity for using catalysts in the steam pipes to ensure a strict H_2O composition.

Another issue is whether the pressure pulses associated with the fusion explosions can be smoothed out enough as seen at the turbines. We don't know how much pressure variation the turbines can withstand.

Pressure Barriers at Fusion chamber Ports

Because beam pipes for a HI accelerator, a laser driver, and a target-injection accelerator normally operate at vacuum, while the fusion chamber in Hydro*Star operates at a pressure of tens of atmospheres, there are very serious interface difficulties at the ports where these beam pipes connect to the fusion chamber. Not only do the ports have to separate the high-pressure and vacuum environments, but they also must allow for a path through the water blanket, with all essential apparatus appropriately shielded with non-activating materials. The design of the ports therefore becomes very difficult.

Because the design of the target-injection accelerator is unknown, we must leave the formidable task of its port design to future studies. The simplest case may be for the injector to operate through the same ports used by the driver beams, but this is far from obvious if we consider the interface difficulties that would result.

For each driver beam port, it may be possible to use a solid barrier with a hole whose size (3 mm) is slightly larger than the focused spot size of the accelerator system (2 mm). Downstream of this barrier, a series of expansion subchambers between baffles immersed in the water blanket should rapidly reduce the steam from the fusion chamber to a moderate pressure (significantly below 1 atm?) provided the subchambers can condense the steam rapidly enough to permit large Prandtl-Meyer expansion angles of the steam entering each subchamber. Studies must be conducted to optimize the design of such baffled subchambers, and ensure the desired thermal-transfer rates to the surrounding 100 C water. Differential pumping (e.g., a series of Roots blowers, to avoid water getting in the pump oil) could then be considered immediately upstream of the beam-entrance barrier in an expansion chamber (not shown in Fig. 1) to form the isolation of the moderate pressure from the beam-tube vacuum.

The differential pumping capacity required can be estimated by assuming that the baffle system reduces the pressure only to 1 atm (760 Torr), and computing the conductance C of a 1.5-m-long pipe with a 3-mm diameter. The conductance is given by

$$C = \frac{A^2 P}{8\pi\eta_v L} = 5305 \frac{\left[A(m^2)\right]^2 P(Torr)}{\eta_v(Pa \cdot s)L(m)} \qquad \text{liters/second} \tag{8}$$

where the pipe area is A, P = 760 Torr, the pipe length is L = 1.5 m, and the steam viscosity is $\eta_v \approx 1.4\text{x}10^{-5}$ Pa-s. The conductance is then 10 l/s, so at 760 Torr, the pumping capacity required is $7.6\text{x}10^3$ Torr-l/s. State-of-the-art oil pumps have a capacity 10 to 100 times this value, and the Nova Roots blowers had a capacity 10 times this value. In addition, the baffle system is likely to reduce the pressure well below 1 atm; moreover, the conductance of the system will be much less than 10 l/s if sonic choked flow is established. In short, the required pumping capacity seems to be well within capabilities, but more study is required to determine more accurate pumping parameters.

These techniques to couple vacuum lines with the chamber would require that the beam be focused before arriving at the outside of the fusion chamber, and be propagated for roughly 5 m of pathlength at its focused state inside the ionized channel formed inside the entrance port and into the fusion chamber. We do not know if it is possible to transport a HI beam in such a manner, but such transport is undoubtedly easier to accomplish for a laser beam. In addition, the prepulse system must somehow be interfaced to operate through this same hole, and all holes must be operated so that they do not ice shut. Moreover, we must worry about the effects of the shock that travels up the baffled system following each fusion pulse, and the rate of erosion of the first upstream 3-mm orifice. These issues have not been addressed for a laser beam as well, so we view these difficulties as some of the most severe in attempting to establish the viability of Hydro*Star.

Driver Beam Propagation Through Ambient Vapor

According to current understanding,[3] heavy ions (Z > 50, A > 130) can propagate through ionized channels if we consider the following constraints on the ambient fusion-chamber vapors:

(1) The ion number density in the ionized channel must be larger than about $3\text{x}10^{16}$ cm^{-3} to suppress micro-instabilities in a neutralized beam (two-stream, hose-type, et cetera), but ballistic propagation without significant charge stripping requires number densities less than 10^{11} cm^{-3}.

(2) The column density of the channel must be small in comparison with the ion range (which is usually selected to be about 0.1 g/cm^2). That is, the column density of the

channel must not be so large that collisional dE/dx losses are comparable to the beam energy.

(3) The column density (i.e., radiation length) of the channel must not be so high that beam emittence is seriously degraded by multiple Coulomb scattering of the ions in the channel.

(4) The channel densities must not be so large that the propagation of the HI beam causes significant ohmic losses in the channel from return currents flowing in response to the induced electric fields.

Even though any discussion of beam instabilities other than the limit imposed by (1) above is outside the scope of this report, more study of beam instabilities is required. Item (4) is also outside the scope of this report. The net result of all of the above constraints for a HI beam, as assessed in 1981,[8] is to expect suitable transport over lengths of <10m for pressures less than 10^{-3} Torr or perhaps in a window from 0.1 to 1 Torr, all at 273 K.

The assumption here is that a prepulse system, composed of an electron, (10-µm?) laser, or HI beam, can blast its way through the ambient fusion-chamber vapors and create the desired ionized channel. The ability to use such a prepulse system depends on many issues, including the following:

(1) How to interface the prepulse system with the HI system prior to entering the HI beam ports on the fusion chamber.
(2) How to focus the prepulse system on the target.
(3) How much energy is lost in coupling the prepulse beam to the water vapor.
(4) How much energy is required to prepare a channel having a suitable density and ionization level.
(5) How much time is required to expand the ambient channel to obtain the required channel densities.
(6) How much energy is lost because of radiation from the hot channel.
(7) How much damage, if any, is done to the target by the prepulse beams.

The energy loss in using a prepulse can be estimated by calculating the amount of energy required to completely dissociate, nearly completely ionize, and heat up each prepulse channel so that expansion of the channel would produce an acceptable ion density, say, 5×10^{16} ions/cm^3. If we assume that the channel diameter is 3 mm with length 5 m, the channel mass is 4.7×10^{-4} kg. Dissociation requires 53 MJ/kg or 0.025 MJ per channel, and complete ionization requires 6720 MJ/kg or 3.2 MJ per channel (but ionization of all levels except the last 739-eV oxygen level requires only 40% of this or 1.3 MJ per channel). If we assume the heated channel will expand adiabatically, we need to heat the vapor to a temperature that scales with the 2/3 power of the number density (assuming a specific heat ratio $\gamma = 5/3$). If 5×10^{16} ions/cm^3 is acceptable, then we need to heat the vapor to roughly $1000(4.5 \times 10^{20}/5 \times 10^{16})^{2/3} = 4.3 \times 10^5$ K = 37 eV, which requires about 1.7 MJ per channel. Thus, each channel can be prepared with a minimum energy of only 3 MJ. This analysis ignores any radiation losses, and assumes that enough time is available for the heated channel to expand. Of course, half of the prepulse beam energy is recoverable with a plant thermal efficiency of 0.50.

Collisional dE/dx losses of the heavy ions in the ionized channel are the most restrictive. Such losses are best discussed in terms of the range of the heavy ions, which is usually chosen to be near 0.1 g/cm^2. If this were the case, we would desire a channel length less than 0.01 g/cm^2. Because each 5-m-length channel is 2.2 g/cm^2, the prepulse would have to expand the channel cylindrically by at least a factor of $(220)^2$, thereby reducing the ion density from 4.5×10^{20} to less than 9.3×10^{15} cm^{-3}. Because we assume that beam micro-instabilities may become bothersome below a few times 10^{16} cm^{-3}, some tradeoff may be necessary between the beam total range and the channel ion density.

Degradation of beam emittence because of multiple Coulomb scatterings of the heavy ions off water-vapor nuclei depends on how the product of the beam size (2 mm) and the rms scattering angle compares to the beam emittence of typically 2 mm mrad.[3] The multiple Coulomb scattering angle in mrad is[9]

$$\Theta = \frac{14.1\ \mathrm{MeV/c}}{p\beta} Z_{\mathrm{in}} \sqrt{\frac{x}{36.1\ \mathrm{g/cm^2}}} \left[1 + \frac{1}{9}\log_{10}\left(\frac{x}{36.1\ \mathrm{g/cm^2}}\right)\right] \qquad (9)$$

where p is the beam momentum in GeV/c, β is the ratio of beam speed to the speed of light, Z_{in} is the charge of the beam, x is the column density of the channel in g/cm^2, and 36.1 g/cm^2 is the radiation length for water. If we assume that Z_{in} is about 70 and that $p\beta$ is about 20 GeV/c, then θ is 1.0 mrad when x is 0.035 g/cm^2 and 0.1 mrad when x is 6.6×10^{-4} g/cm^2. For a 5-m length channel, these values correspond to vapor densities of 7.0×10^{-5} g/cm^3 (7.0×10^{18} ions/cm^3) and 1.3×10^{-6} g/cm^3 (1.3×10^{17} ions/cm^3). Therefore, because the scattering contribution adds to the beam emittence in quadrature, multiple Coulomb scattering will not significantly degrade the beam if the channel ion density is less than 10^{17} to 10^{18} ions/cm^3. Consequently, ionizational dE/dx losses are more restrictive than scattering losses.

For the discussion here, we will assume that HI prepulsing is feasible, preferably using the HI beam system itself, and that the required channel density is 5×10^{16} ions/cm^3. The parameters required for a laser pre-pulse system must be addressed in a future study, but we believe that pre-pulsing may be more easily accomplished for a laser beam than for a HI beam because higher residual chamber gas densities can be permitted for laser propagation.

Target Injection Through Ambient Vapor

Target injection into a chamber operating at about 20 atm has not been studied, and must therefore be addressed. Issues include (1) thermal control for cryogenic targets, (2) deflective instabilities in propagation through a possibly turbulent ambient vapor, (3) interface of the injector to the fusion chamber, (4) deceleration of the target in propagating through the fusion chamber, and (5) suitable alignment and tracking techniques.

An estimate of the problems to be encountered because of the deceleration of the target after injection can be obtained by computing the terminal velocity of a target injected vertically using gravity. The terminal velocity is[10]

$$v_T = \frac{2r^2 g\left(\rho_{tg} - \rho_{vp}\right)}{9\eta_v} \tag{10}$$

where r is the radius of the target (let's assume it is 1 cm), g is the acceleration due to gravity (980 cm/s^2), ρ_{tg} is the effective target density (let's assume 0.1 g/cm^3), ρ_{vp} is the vapor density (4.4x10^{-3} g/cm^3), and η_v is the viscosity of the vapor (about 1.4x10^{-4} g/cm s). With these assumptions, the terminal velocity is 1.6 m/ms. Thus, deceleration is expected to be an issue, but not a significant issue.

Neutron Shielding for Driver Beam Ports and Vent Tubes

There is no problem introducing a bend at the last HI focusing magnet so that upstream driver components are not in a direct line-of-sight to the target. Nevertheless, neutron scattering can result in leakage of neutrons along escape paths (vent tubes, beam ports). Therefore, port designs must attempt to minimize this leakage through adequate additional shielding, and must account for the possibility of reduced lifetimes of components exposed to the neutron fluence. Optimum design of such additional shielding is straight forward, but nontrivial. Similar comments apply for a laser driver.

First Wall Stresses

The possibility of high structural wall stresses is a serious problem for Hydro*Star. The fusion yield per target is 2.8 GJ, or 2/3 ton TNT-equivalent. This is up to 3 times more than planned for the LLNL LMF chamber. The fact that the explosion occurs at a pressure of about 20 atm makes the stresses even higher, because the transfer of energy from the target to the blanket (and finally to the wall) is primarily through hydrodynamic shocks, not radiation. However, the shocks are attenuated considerably by propagation through the water vapor because complete dissociation of water requires 53 MJ/kg, and complete first ionization requires 220 MJ/kg, and up to 500 kg of ambient vapor is produced in the chamber prior to venting. Nevertheless, similar dissociation and ionization energies apply for air (e.g., 33.8 MJ/kg to dissociate nitrogen, 100 MJ/kg to first-ionize nitrogen), and experience from explosions in air suggest that high stresses may be involved. In any case, we know of no calculations of the shocks transferred to a blanket at conditions anywhere near those applicable here, so calculations must be forthcoming.

If the blanket can be operated with vapor bubbles introduced in whatever manner possible, the structural wall stresses will probably be well within structural limits for chamber radii exceeding roughly 3 m.[11] The worst case possible is thus a water blanket without any bubbles. For such a system, the momentum impulse transferred to the structural wall is actually less than produced through shock impact at the inner surface of the water, because of the increase in area of the structural wall. The impulse on the structural wall increases as the inner radius of the water is decreased, and would become intolerable at some radius that is dependent on target yield. However, radii larger than about 3 m should be sufficient to reduce all stresses to a manageable level because shocks attenuate to the uni-axial-strain levels before traveling 1 cm in most liquid and solid materials. Although interior post-fusion pressures do rise briefly to very high values, no acceleration of the water annulus is possible, as there would be for interior annuli or jet structures.

Another serious problem is the potential for stress corrosion cracking at welds in the structural wall. Because of experience with G.E.'s boiling water (fission) reactor, it was discovered that chloride (and molybdenum, etc.) ions originally at low concentration (parts per billion levels) slowly increase in water that is being vaporized until the conductivity allows carbon to be extracted from the heat-affected zones near the welds in a structural wall composed of ordinary steels. The carbon then reacts with the chromium, and the chromium removal leads to corrosion. However, they discovered that use of low-carbon steels (series 300 steels with carbon less than 0.04 ppb) prevents the occurrence of this problem. Therefore, Hydro*Star must use such low-carbon steels for any surfaces in contact with the water being vaporized in the fusion chamber to avoid the stress-corrosion cracking problems. With use of such steels, stress-corrosion cracking should not be a problem.

Blanket Purity &Waste-Stream Cleanup

Radiological management and waste-stream cleanup for the water blanket involves serious issues, not from the water itself, but from contaminants added to the water. The induced activity in the water itself arises primarily though ^{14}C production off ^{17}O via $^{17}O(n,\alpha)^{14}C$. We have not yet estimated the induced activity from this process, but we don't expect it to present a serious problem.

For a plant output power P, unburned tritium will get into the water from the fuel targets at a rate

$$R_T = \frac{P\,(1+f)}{\varepsilon_{th} M E_{TN} \Phi_{DD}} \left(1 - \Phi_{DT}\right) \frac{m_{DT}}{m_{DD}} \qquad (11)$$

This yields about 1/50 mg/s (0.2 Ci/s) for P = 1 GW, f = 0.10, ε_{th} = 0.50, E_{TN} = 347 MJ/mg, Φ_{DD} = 0.20, Φ_{DT} = 0.33, and fuel mass ratio m_{DT}/m_{DD} = 1/1000 (which is only approximate). There may also be some tritium produced by the DD reactions that does not burn, and if so, the tritium buildup could be faster than 0.2 Ci/s.

A blanket 1.5 m thick at a chamber radius R = 4 m has a mass of 300 metric tons (300 m^3), which we will double to 600 metric tons (600 m^3) to account for storage and piping volume. Tritiated water is hazardous to humans only if ingested, because it emits a positron that is easily stopped by clothing et cetera. According to 10CFR20 (Appendix B, Table II, Col. 2), tritiated water is safe to spill directly on the ground at a concentration less than 3 x 10^{-3} Ci/m^3. At 0.2 Ci/s, this concentration is reached after only 9 seconds of equivalent averaged operation. Tritium extraction facilities are therefore necessary. The current planning for the LLNL LMF design is to purify the LMF waste stream only to 1 Ci/m^3, and this concentration is reached in Hydro*Star after 50 minutes of operation. Methods to extract the tritium for reuse in the targets must of course be developed, and the level to which the tritium should be extracted with such methods must be determined from future investigation. Containment of the tritium in water, however, is not only the safest from the standpoint of a biological hazard, but the easiest for processing.

Of greater concern is the radioactive target debris that will end up in the water. The full impact of this debris must await a description of the target, but about 100 metric tons of substance per gram of target material must be processed per year of plant operation. If some of this is activated and/or toxic, considerable expense could be involved in waste-stream processing.

Another potential problem that cannot be ignored is the buildup of contaminants in the water because they are left behind when the water evaporates, as discussed for stress-corrosion cracking in boiling-water reactors in the section above on first-wall stresses. For Hydro*Star, we need to assess whether such buildup is an issue, or whether recirculation of the water will prevent buildup. We also need to establish whether the surface of the blanket is exposed to x rays, and if so, whether the contaminants would also be vaporized, thereby excluding the contaminant issue as a problem for Hydro*Star.

Vent and Steam Piping

The interface of the steam vents with the fusion chamber must allow for adequate neutron and x-ray shielding of piping and exterior components. In particular, the vents must not be an avenue for the escape of neutrons otherwise contained within the blanket. There should be no problem, however, with the operating temperature being 900 K and the operating pressure being tens of atm because standard steam turbines operate at this temperature and well above this pressure (e.g., 1000-2000 psig = 68 to 136 atm typically and 5000 psig = 340 atm maximum).[7] Nevertheless, there could be problems with oxygen corrosion or problems similar to the stress-corrosion cracking difficulties discussed above.

Radioactivity In & Maintenance Of the Turbines

Because hydrogen tends to be absorbed by various materials and can cause embrittlement, it is generally not good to operate turbines with hydrogen. It is also not good to have the turbines operating with a mixture of H_2 and O_2, which may be explosive. Thus, it would be best if the chamber effluent were merely steam upon entering the turbines. Because tritium will be present, some tritium will likely penetrate the turbine blades and require personnel to be suited up during normal turbine maintenance. Although it might be nice to avoid such procedures, there would be no serious threat to personnel as a result of such tritium buildup in the turbines. It might even be possible to flush the turbines with water or some other substance and remove part of the tritium, but other radioactive debris can probably be removed with such procedures more easily than forms of hydrogen. Nevertheless, we do not view the tritium buildup as a problem serious enough to warrant the introduction of a heat exchanger, which would significantly reduce thermal efficiency.

Turbine Temperature & Plant Availability

The standard operating temperatures for steam turbines is approximately 625 C = 900 K, although state-of-the-art turbines operate near 1000 K. The higher the turbine temperature, the lower the plant availability because of down time to fix turbine components.

Therefore, after making allowance for future improvements in turbine design, a systems study must be conducted to determine the tradeoff between higher operating temperatures at the turbine to obtain high plant thermal efficiencies and the desire to maintain high plant availability.

Tritium Breeding vs Purchase of Tritium

Only 1/3 of the tritium need be purchased, after tritiated-water recycling begins, and at 0.01 mg/s, this amounts to only 315 grams (1.3 liter) per year of operation. Because the cost of tritium is roughly $10,000.00 per gram, the cost of the tritium is $3 million per year. Although this is only about 1% of the gross electricity sales, it is non-negligible. We should therefore study whether some form of breeding is possible in the water. For instance, LiH or some other compound of lithium might be acceptable if it can be dissolved in the water, and if it does not disrupt the vaporization of the water at the blanket or the condensation of the vapor in the turbines and final heat exchanger, and if it does not cause buildup problems as discussed in the section above on First Wall Stresses. Further investigation is required.

Startup Procedures

Because the water blanket in Hydro*Star is stabilized dynamically, with the input flow balanced by fusion vaporization, the blanket must be gradually established upon plant startup after any down time. Future studies must address how this can best be accomplished, and to establish the necessary procedures.

Hydro*Star Reprate

Because Hydro*Star operates by *not* condensing the vaporized blanket material, contrary to other designs, the reprate of the facility is not as constrained by the time to cool and condense the vaporized wall materials (and its risk is not as affected by the current uncertainties in the physics of condensation). A future study must therefore be conducted to determine what else will limit the reprate. It may be the energy needed to clear channels for the driver beams, because higher reprates correspond to higher chamber pressures (at a given chamber radius). In any case, because the reprate can be increased significantly relative to other ICF fusion-chamber designs, detailed studies are required to determine how much the projected cost of electricity (COE) can be reduced by higher reprate operation. Specifically, previously published generic estimates[12] showing that the COE is minimum for reprates of 25 to 30 Hz cannot be used for Hydro*Star because of the detailed nonlinear nature of a real driver, especially for a DPSSL. Besides, the generic case has a very broad minimum in which the COE at 5 to 10 Hz is only about 5 to 10% higher than at 25 to 30 Hz. In addition, as can be ascertained from the current rise in costs of producing electricity and the results of the next section, just about any reasonable reprate is acceptable for Hydro*Star.

Therefore, the reprate of Hydro*Star can be determined from the consideration of several critical factors. First, the reprate must be fast enough to avoid gravitational distortion of the inner surface of the water blanket. Hydro*Star can hence be reprated as fast as is needed to keep the blanket operation within acceptable requirements. Second, the desired dynamical water-vapor chemistry must be compatible with turbine operation in addition to the vapor pressure and temperature. These dynamical parameters change with reprate. Third, the size of the plant might be affected by fusion economics, especially the desire of utility companies for a certain size of plant. The optimum overall reprate can be determined based on factors such as these.

Cost of Electricity (COE)

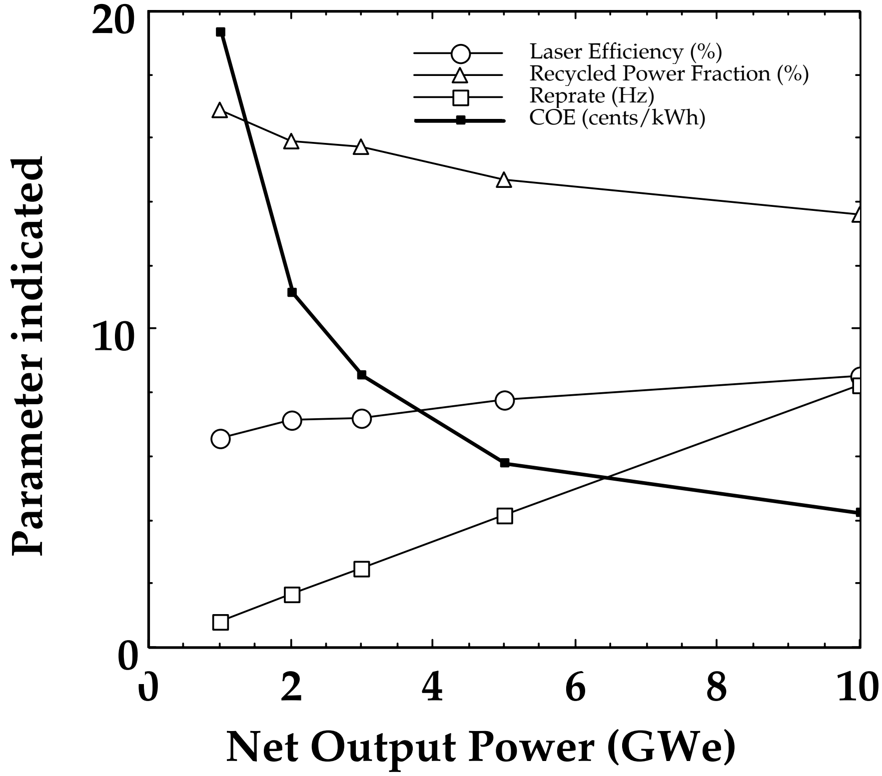
We report here the results of an initial study of how COE and plant size can vary with reprate for the case of a DPSSL driver. For this purpose, we started by assuming that the reprate for a plant with 1 GWe net electrical output would be identical to that required for the HI plant having the features assumed in this report. Thus, for Hydro*Star, every 0.826 Hz corresponds to 1 GWe of electrical power. We hence doubled this basic reprate to obtain a 2-GWe plant, tripled it for a 3-GWe plant, and so forth. Figure 3 displays the results, as obtained using our DPSSL*IFE systems code with COE in constant 1991 dollars.[13] Note that COEs between 4 and 20 ¢/kWh are obtainable for plant sizes of up 10 GWe for laser efficiencies of 6 to 9%. All cases have 1200 to 1400 laser beams. For 1 GWe, it is interesting to note that the simple analysis given by Eq. (1) incorrectly indicates a target gain of 168 and a recycled power fraction of 11.8% for a driver energy of 16.1 MJ.

In contrast to the results in Fig. 3, note that if reprate and driver energy are allowed to vary independently, the minimum COE for 1 GWe occurs for a reprate of 3 Hz, a 30% recycled power fraction, a target gain G of 63, and a COE of 14 ¢/kWh. With this same type of freedom, but using completely DT fuel, the minimum COE of 7 ¢/kWh occurs at 3 Hz with only 192 beams. Thus, the results depend on the constraints and the way the optimum is obtained.

Conclusions

We have described a new IFE fusion-chamber system called Hydro*Star that uses DD targets ignited with DT hot spots, and have described a multitude of physics and engineering issues that must be addressed before Hydro*Star can be considered to be a viable concept. Nevertheless, Hydro*Star has so many significant advantages over other IFE chamber concepts that it seems worthwhile to pursue the additional studies that will address these and other concerns. The result would be a much safer fusion plant with greater appeal to the general public because the main fluid used is simply hot water, which is of course nontoxic, nonradioactive, nonflammable, and safe for the environment. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

Figure 3 Variation of COE and other plant features with reprate for a DPSSL plant under the assumption of 0.826 Hz per GWe of plant net output power



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